The River Machine: A Conceptual Model Integrating Fish Movement and Habitat, Fluvial Geomorphology, Fluid Dynamics, and Biogeochemical Cycling

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and many others

Thinking about Fish at Ecosystem Scales
Presentation Organization

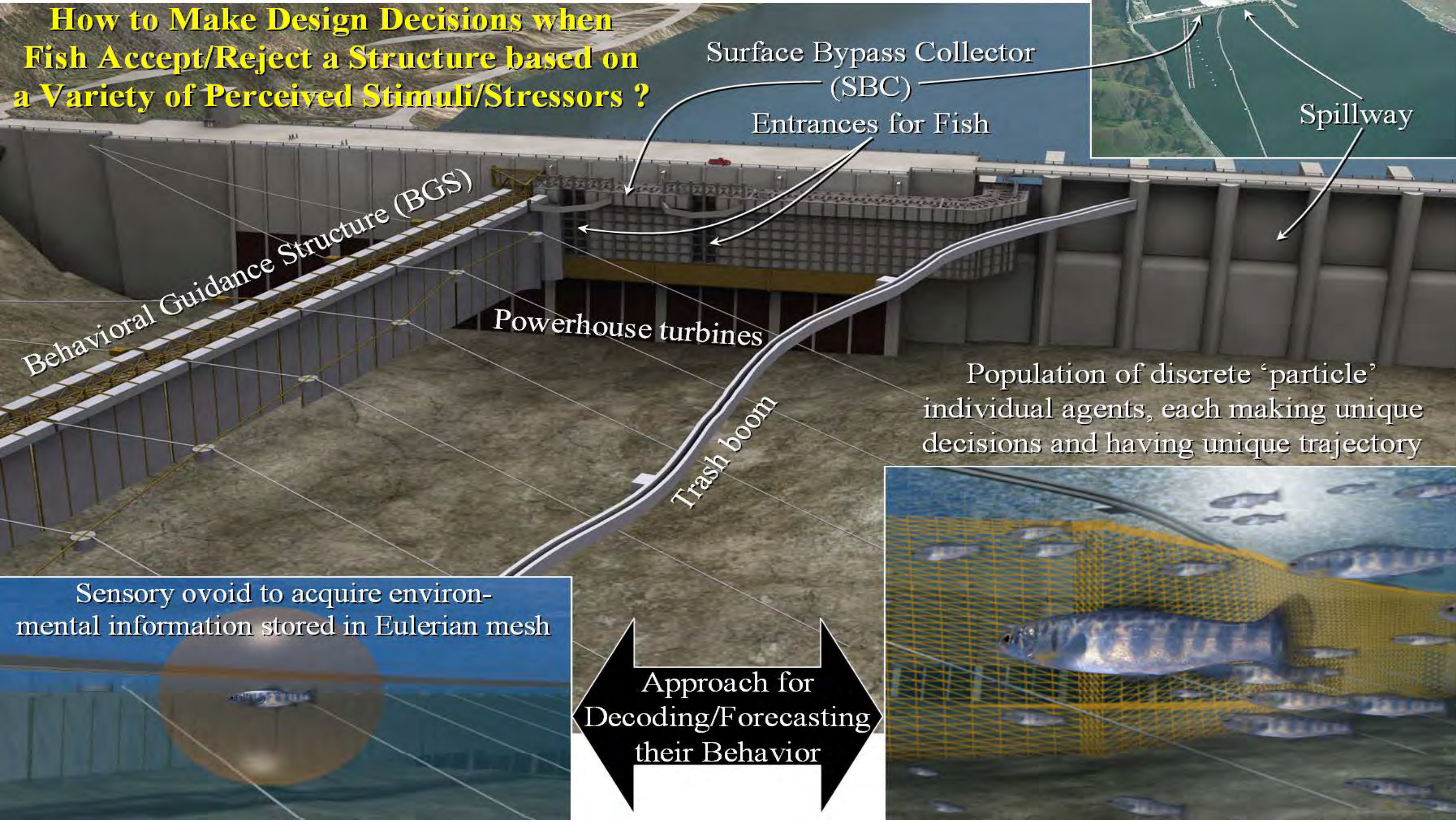
Logical Progression

- **Hydrodynamic variables used by juvenile salmon during emigration**
  - Velocity Magnitude Gradient (cue) and Velocity Magnitude (direction)
  - Huge tagging data sets from Pacific NW USA emigrating salmon / not likely to be duplicated
  - Salmon good model system for understanding fish movement
  - Goodwin et al. 2006

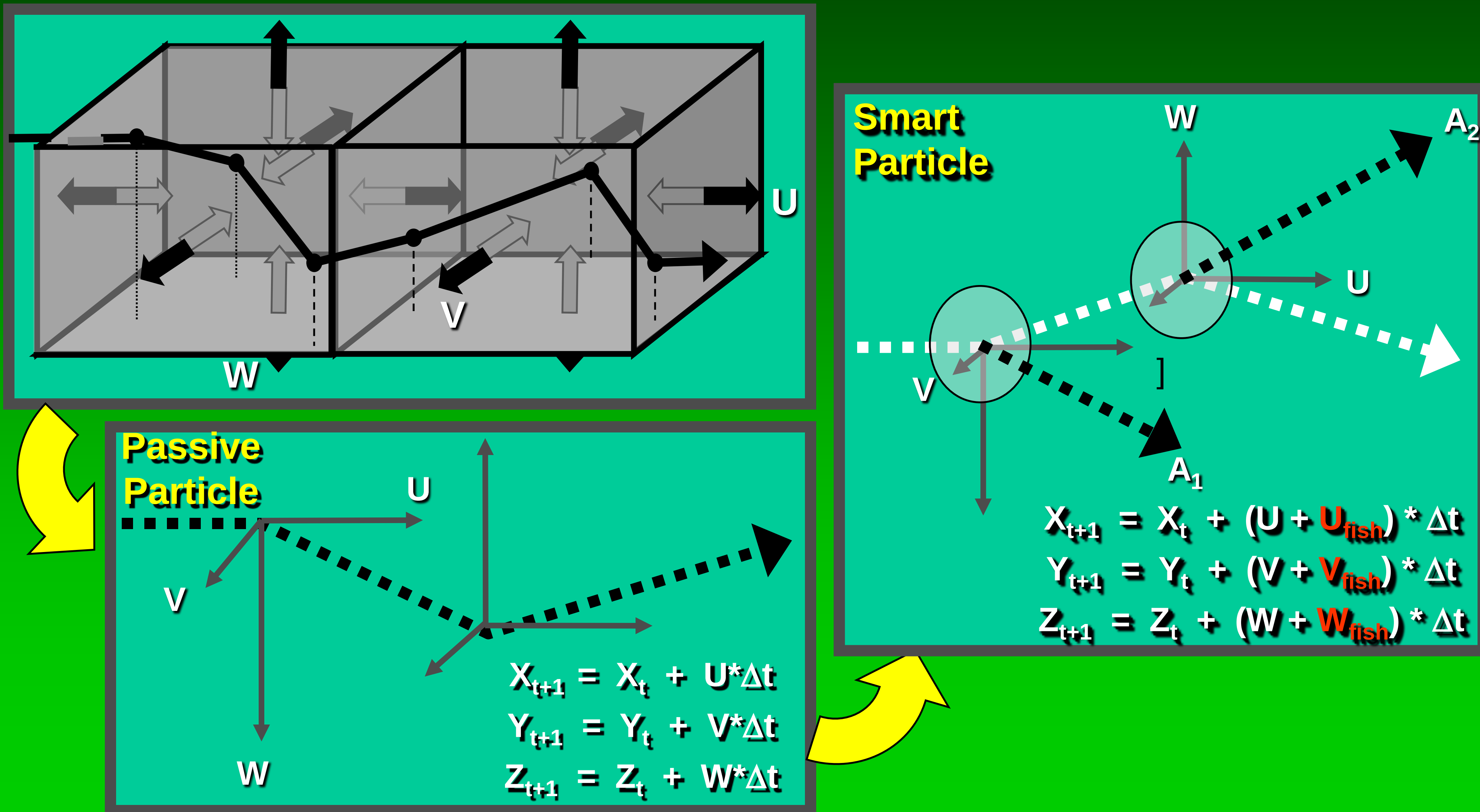
- **These two variables used by fish to create a "hydraulic road map" in unimpaired streams**
  - Two variables integrated together (+scale) relate to the solid features in a channel
  - Fish form a "hydraulic snapshot" of their surrounds to choose direction or location
  - Nestler et al. 2008

- **Cues are related to fluvial geomorphology and biogeochemical cycling**
  - Migrating fish locate in time and space to take advantage of work performed by the river i.e., they find biogeochemical hotspots and hot moments (River Machine Concept).
  - Nestler et al. 2012

A Common Problem



The Method: Integrate Eulerian, Lagrangian, & Agent-Based Frameworks = ELAMs



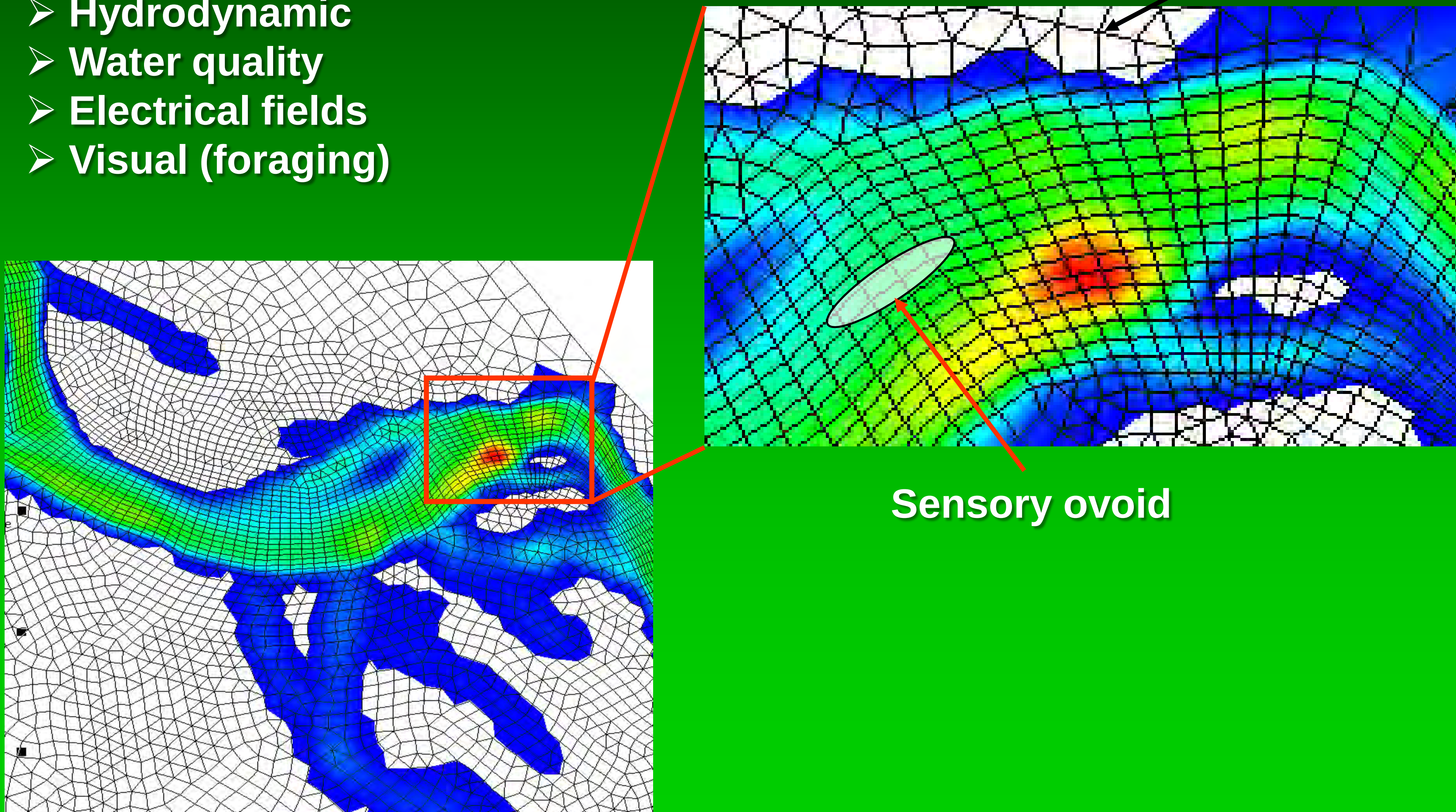
$$X_{t+1} = X_t + U^*\Delta t$$
$$Y_{t+1} = Y_t + V^*\Delta t$$
$$Z_{t+1} = Z_t + W^*\Delta t$$

$$X_{t+1} = X_t + (U + U_{fish}) * \Delta t$$
$$Y_{t+1} = Y_t + (V + V_{fish}) * \Delta t$$
$$Z_{t+1} = Z_t + (W + W_{fish}) * \Delta t$$

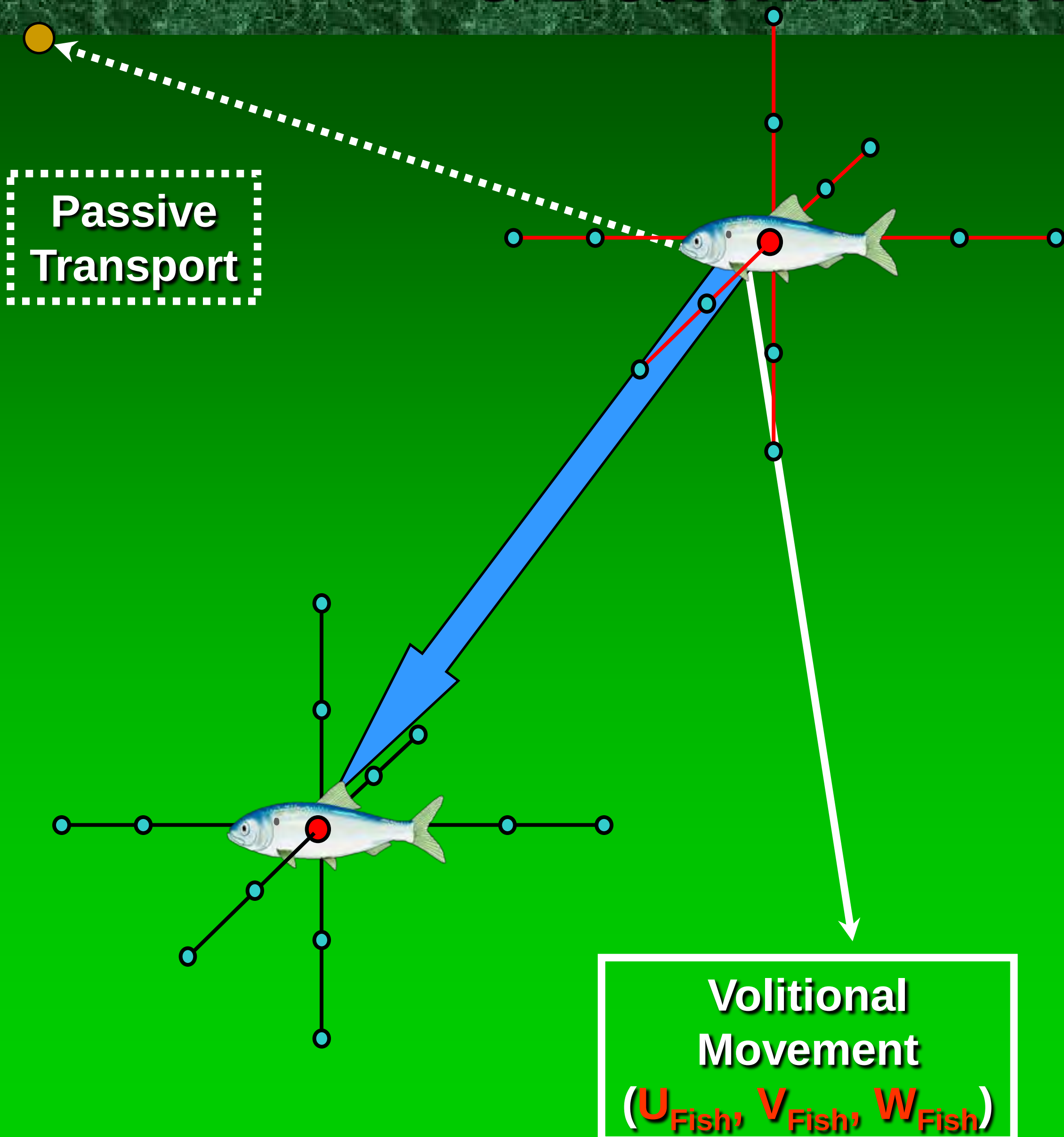
Operationally……

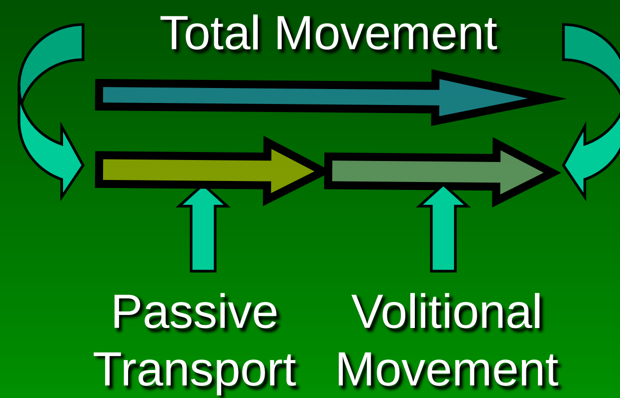
Stimulus (Cue) Categories:

- Hydrodynamic
- Water quality
- Electrical fields
- Visual (foraging)

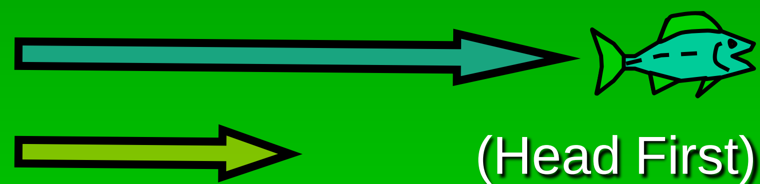


Separate Passive Transport & Volitional Swimming & Determine Swim Direction

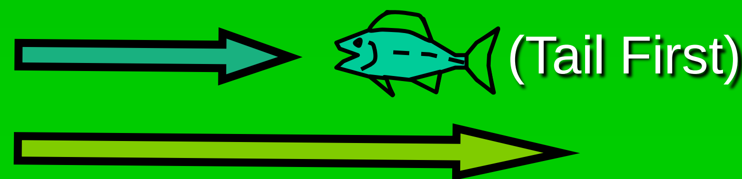




Swims with flow if total movement > passive transport:



Swims against flow if total movement < passive transport:



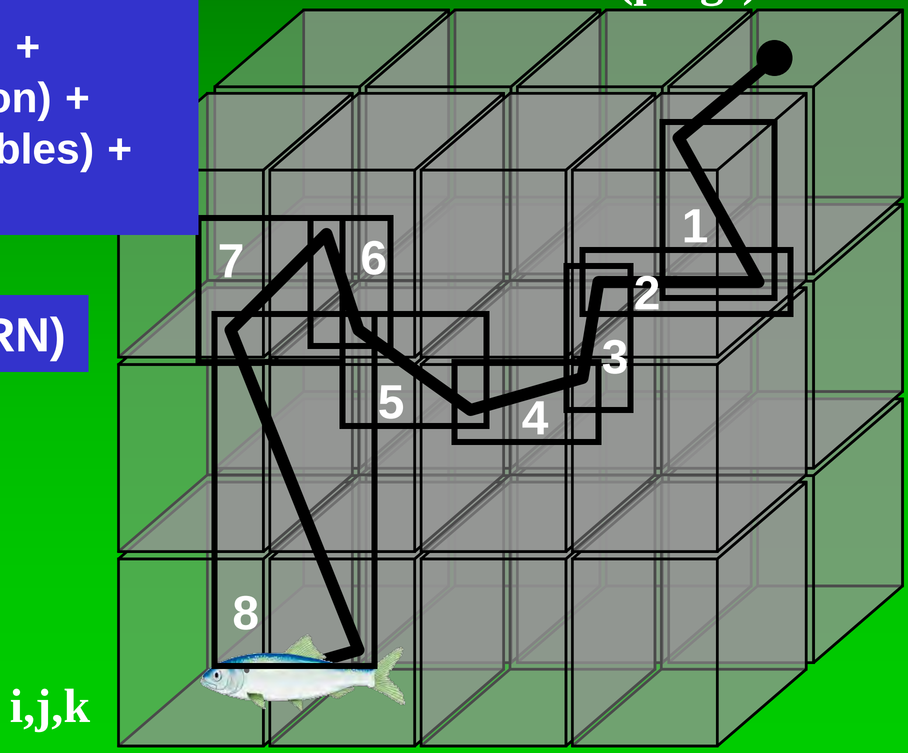
“Governing Equation” for Short Time Steps:

New Position$_x$ =
Old Position$_x$ + passive transport$_x$ + ε_x + biases$_x$ + volitional swimming$_{orientationi}$ + $\varepsilon_{orientation}$

Orientation$_i$=
α_1 +
β_1*(velocity) +
β_2*(acceleration) +
β_3*(turbulence intensity) +
β_4*(turbulence dissipation) +
β_i*(other hydraulic variables) +
β_j*(secondary variables)

(0.65 * Var) + (0.35 * RN)

Fish Track comprised of Observations (pings) 1-8



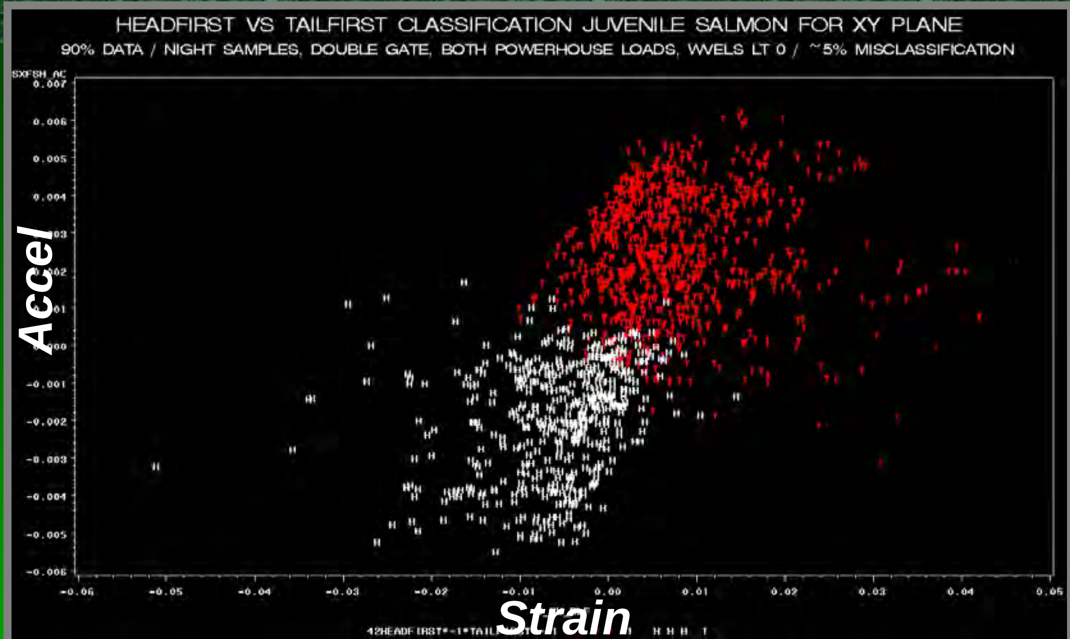
Volitional swimming$_i$=
α_1 +
β_1*(velocity) +
β_2*(acceleration) +
β_3*(turbulence intensity) +
β_4*(turbulence dissipation) +
β_i*(other hydraulic variables) +
β_j*(secondary variables)

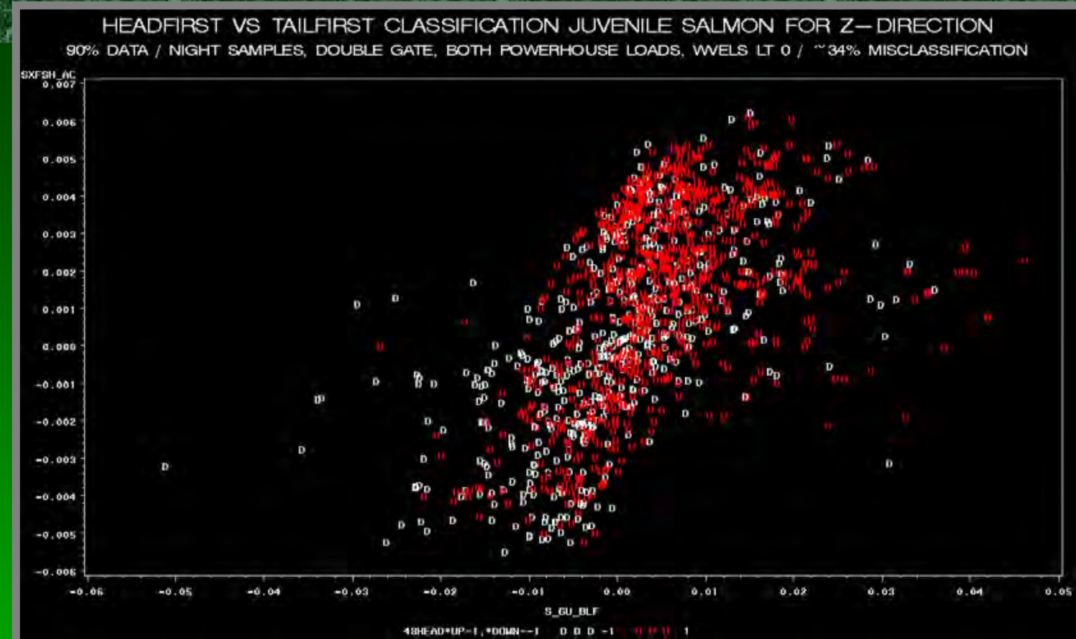
DV=α + (β_1 x INDV1) +
(β_2 x INDV2) + etc
Where :

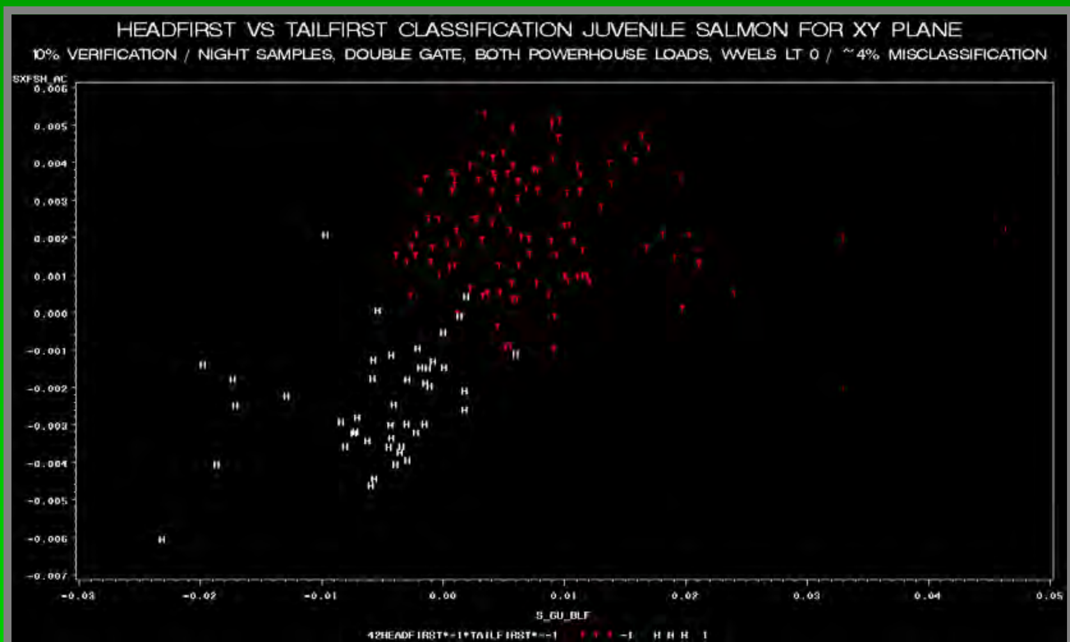
$$DV= \boxed{a} + b + c + d$$
$$INDV1= \boxed{a} + f + g + \boxed{q}$$
$$INDV2= \boxed{a} + v + c + \boxed{q}$$

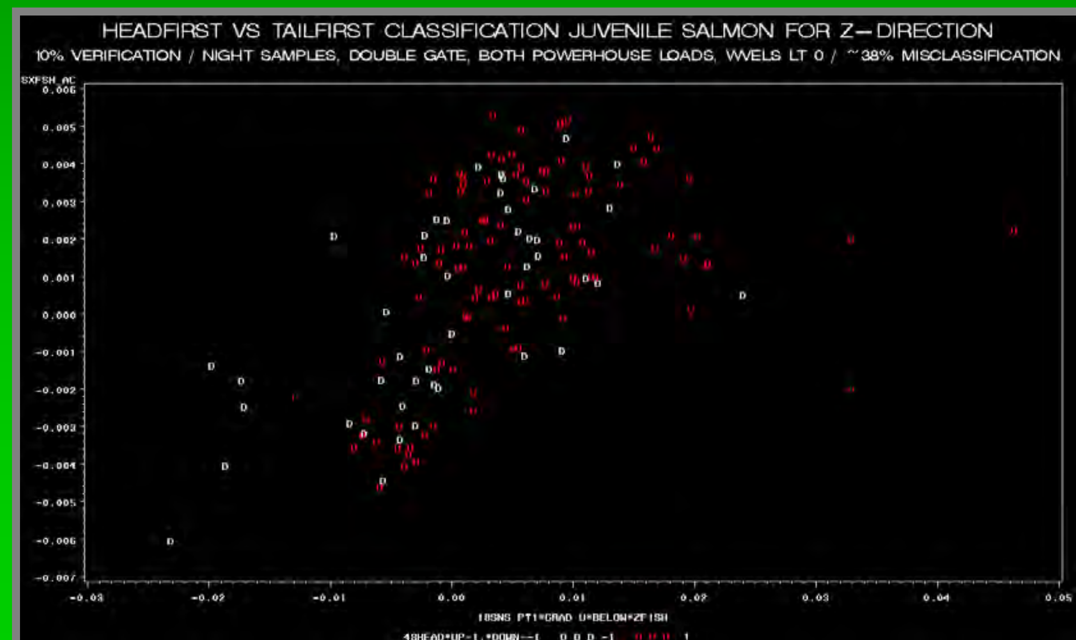
Spurious Auto-Correlation
Non-independent Variables
Serial Auto-Correlation

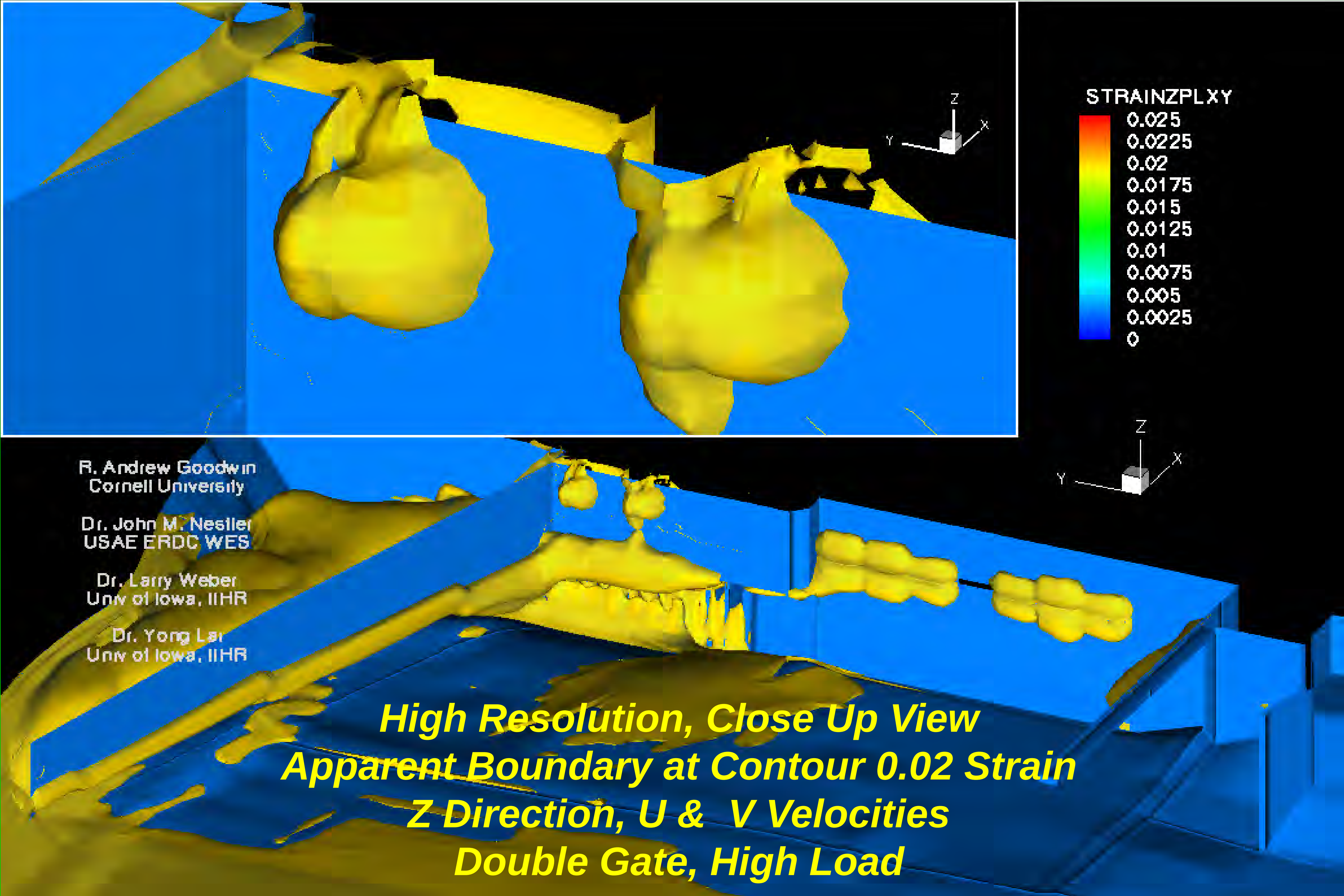
Discriminate Analysis







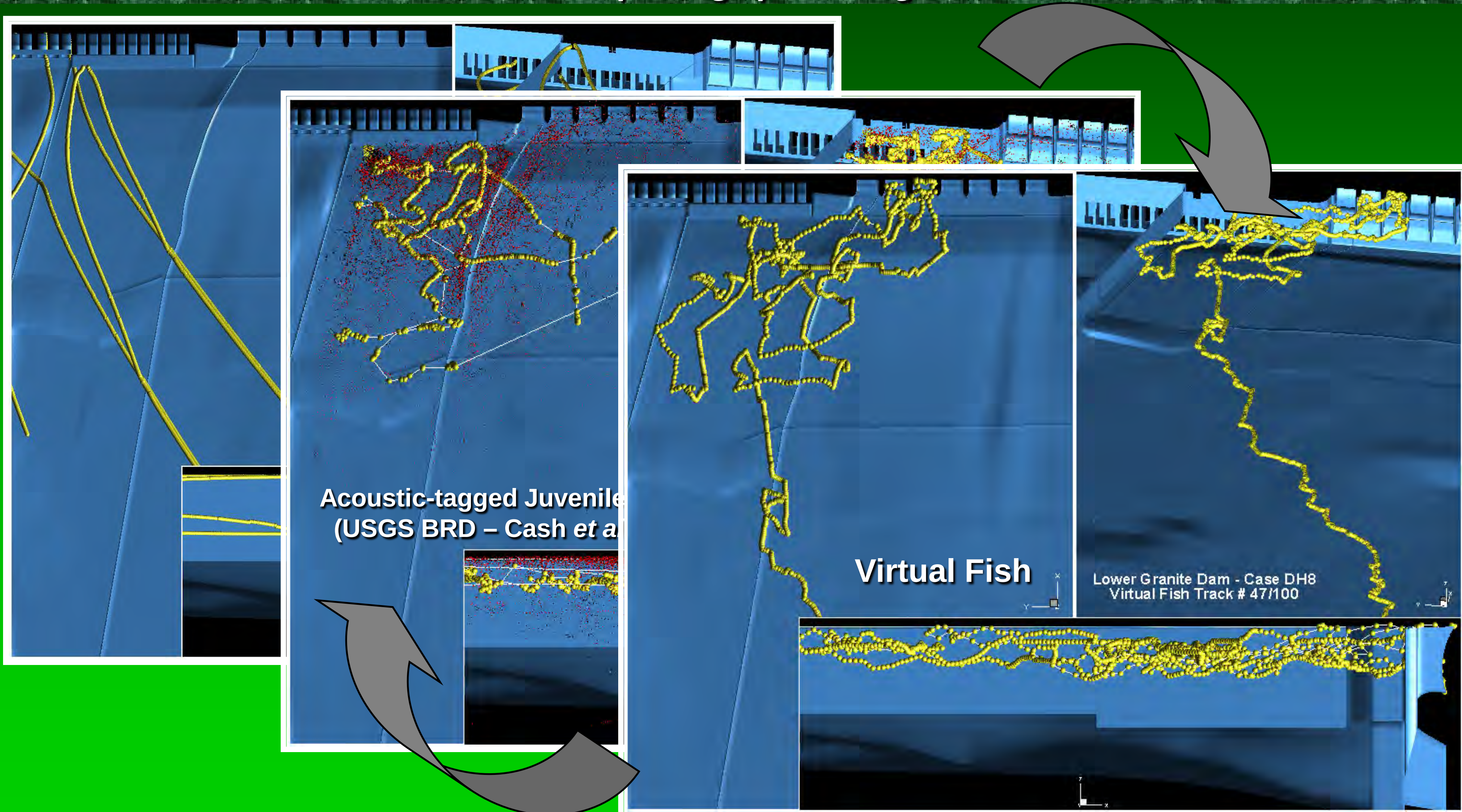



STRAINZPLXY
0.025
0.0225
0.02
0.0175
0.015
0.0125
0.01
0.0075
0.005
0.0025
0
Z
Y
X
R. Andrew Goodwin
Cornell University
Dr. John M. Nestler
USAE ERDC WES
Dr. Larry Weber
Univ of Iowa, IIHR
Dr. Yong Lai
Univ of Iowa, IIHR
High Resolution, Close Up View
Apparent Boundary at Contour 0.02 Strain
Z Direction, U & V Velocities
Double Gate, High Load

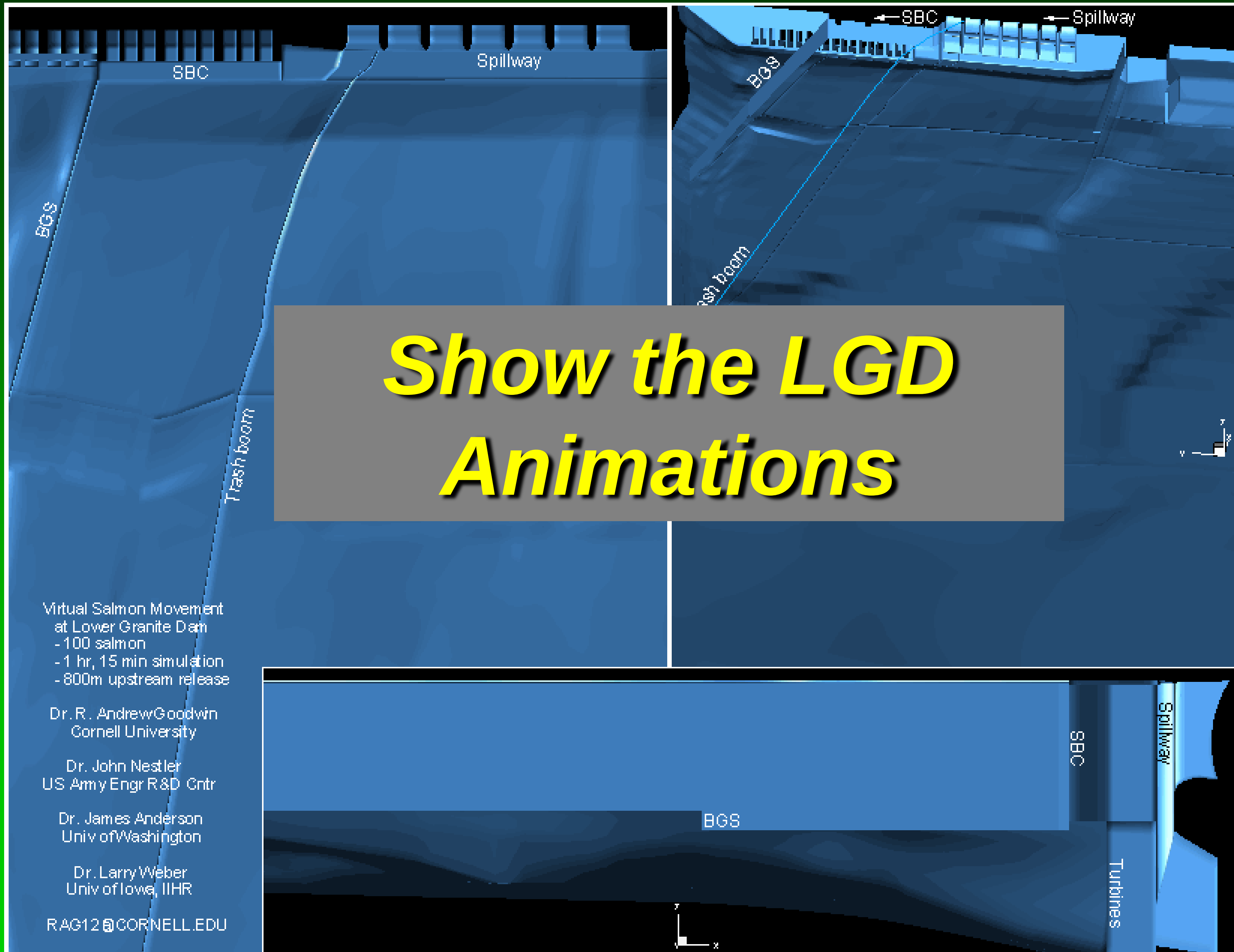
Calibration Approach:

1 - Match salient features of individual traces

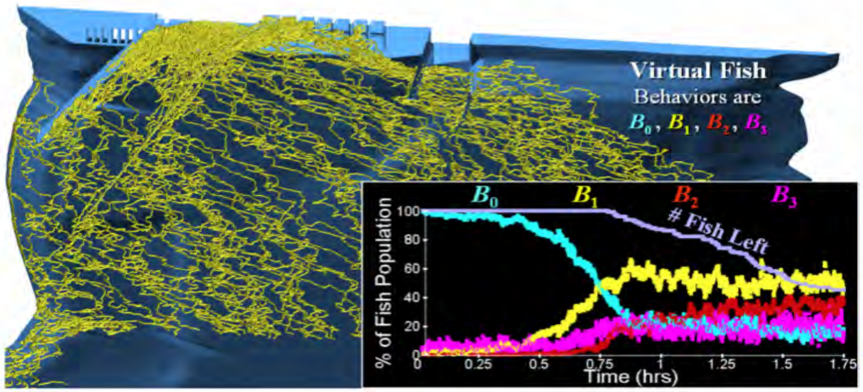
2 - Refine with passage percentages

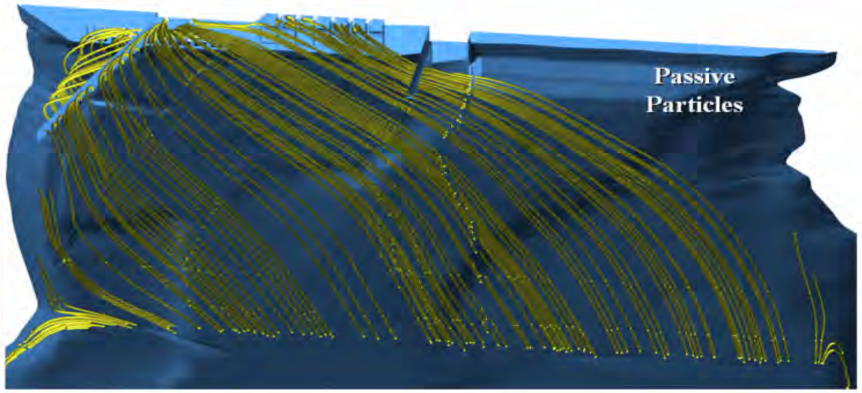


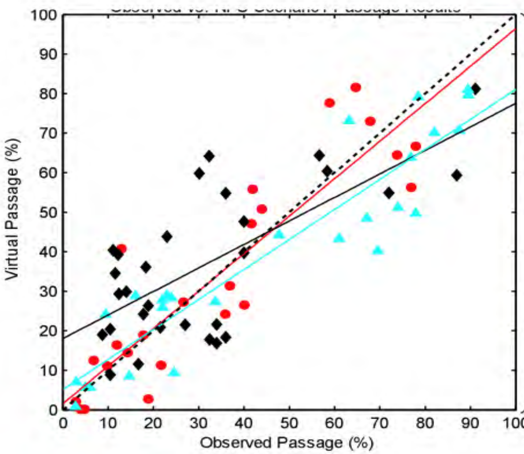
Show the LGD Animations



How Well Does it Work ?





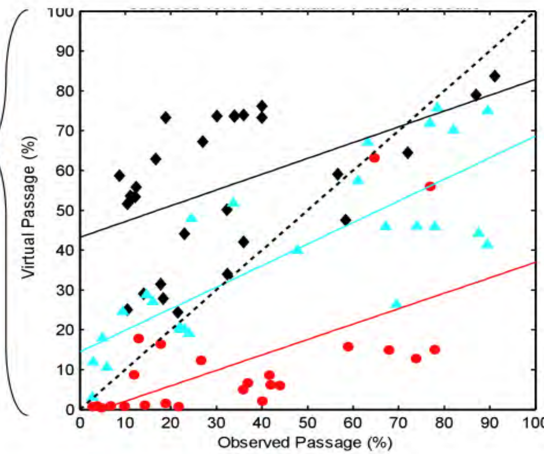


NFS Version 11 (*Best_1*)

Analysis Including: ALL					
Linear Model					Custom
Slope	r^2	RMSE	Intercept	RMSE	Metric
Optimum	Optimum	Optimum	Optimum	Optimum	Optimum
1.0	1.0	0	0	0.0000	1.000
0.9484	0.8058	11.9105	1.5763		
0.5946	0.49	13.8216	18.0503	11.7837	0.777
0.759	0.8668	9.6191	5.1462		

Passive Particles

Analysis Including: ALL					
Linear Model					Custom
Slope	r^2	RMSE	Intercept	RMSE	Metric
Optimum	Optimum	Optimum	Optimum	Optimum	Optimum
1.0	1.0	0	0	0	1.0
0.3875	0.3667	13.0279	-1.8218		
0.3965	0.2485	15.7099	43.2033	14.00903	0.416
0.5417	0.6346	13.2893	14.4342		



Bypass | Powerhouse | Spillway
Linear (Bypass) | Linear (Powerhouse) | Linear (Spillway)

All Dams

(LGR, IHD, TDA, WAN, PRD)

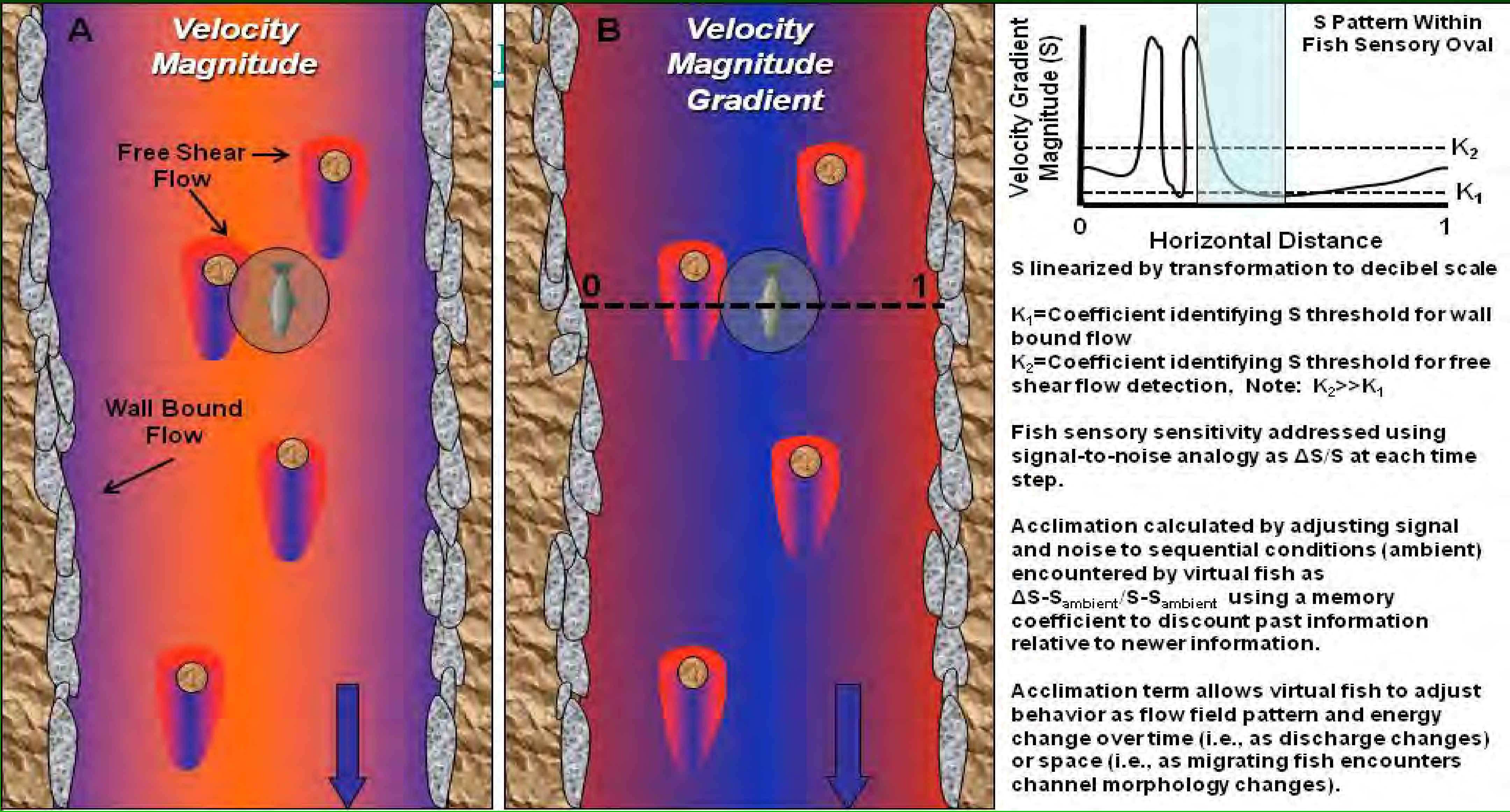
See
dy W
it Fi

- What Causes Flow Pattern in Streams?
  - Flow Resistance - without it there is nothing to change a unit volume of water once it is set into motion by gravity.

- Are There Different Types of Flow Resistance?
  - Four total, but two for steady-state
  - Friction resistance (skin friction)
  - Form resistance (distortion resistance)

- Minimum Hydraulic Information Separating Q Resistance?
- Should lead to conceptual model for movement cue.

Behavioral Rule & Natural HydroGeomorphology



S linearized by transformation to decibel scale

K_1=Coefficient identifying S threshold for wall bound flow
K_2=Coefficient identifying S threshold for free shear flow detection. Note: $K_2 >> K_1$

Fish sensory sensitivity addressed using signal-to-noise analogy as ΔS/S at each time step.

Acclimation calculated by adjusting signal and noise to sequential conditions (ambient) encountered by virtual fish as $\Delta S\text{-}S_{ambient}/S\text{-}S_{ambient}$ using a memory coefficient to discount past information relative to newer information.

Acclimation term allows virtual fish to adjust behavior as flow field pattern and energy change over time (i.e., as discharge changes) or space (i.e., as migrating fish encounters channel morphology changes).

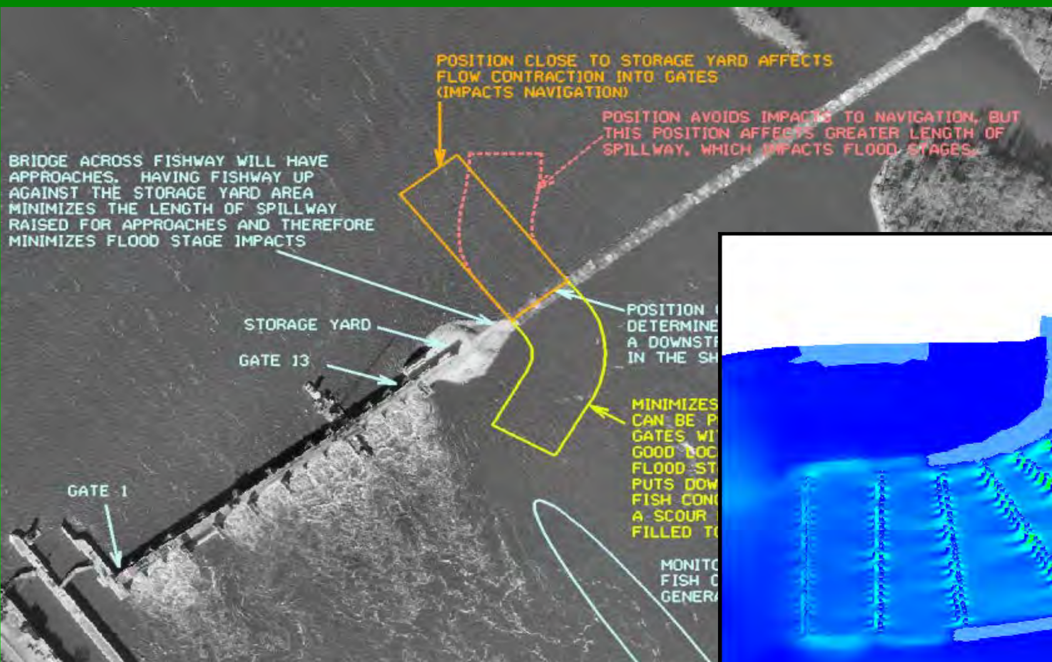
Goodwin et al. 2006

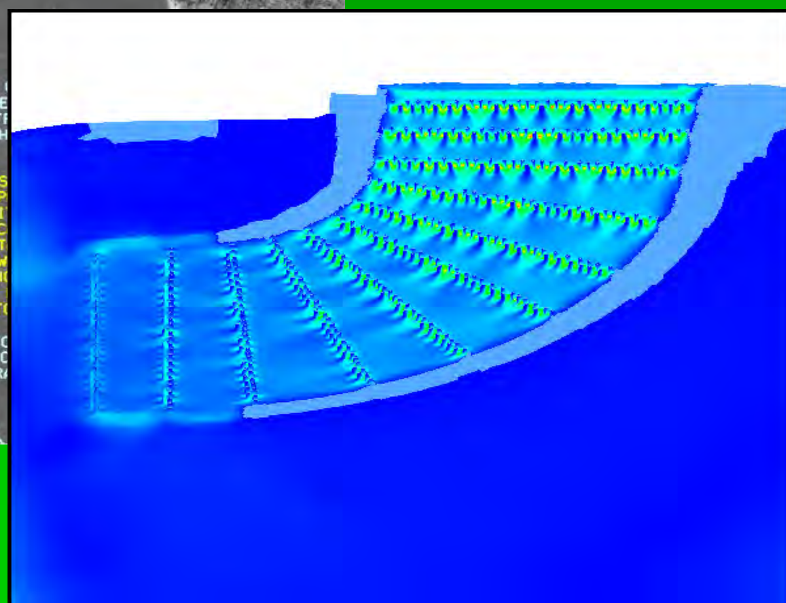
Apply to Different System - Mississippi

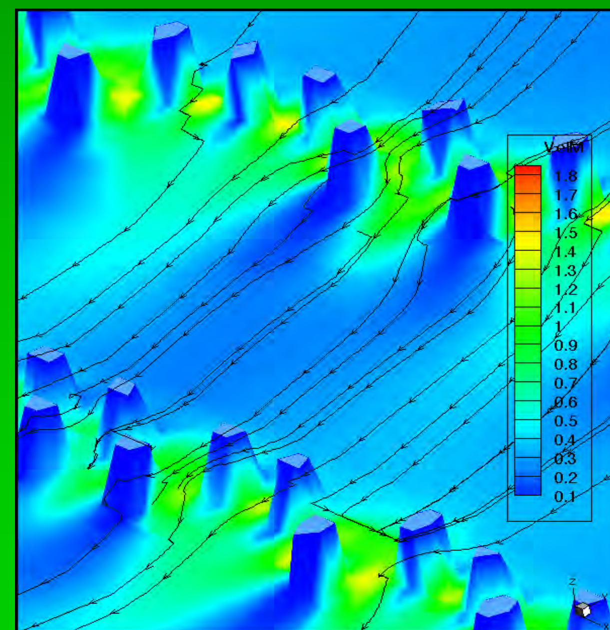
- Concrete portion is 373.1 m long with three roller gates and ten tainter gates.
- Submersible earthen dike 487.7 m long connected to levee.
- Main lock is 33.5 m wide by 182.9 m long
- Incomplete auxiliary lock.

Proposed fish ladder

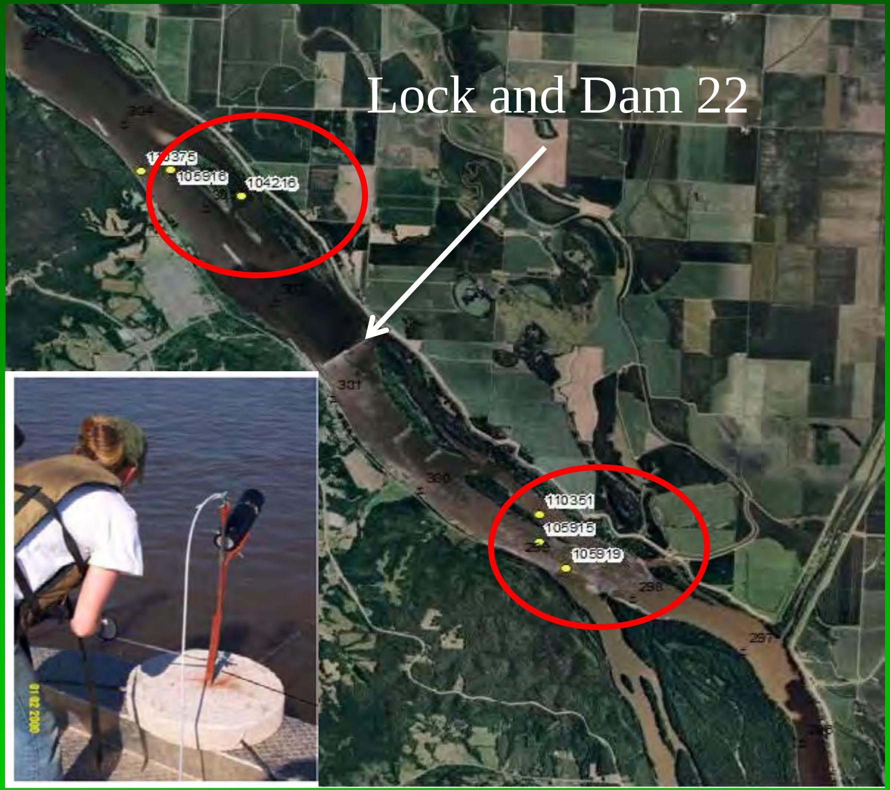
- 61 m bottom width, 152 m total length
- 1.5 m deep pool
- 0.6 m deep, 0.3 m drop riffles
- 1.5 m diameter boulders at 1.2 to 1.8 m spacing
- Rule changes – default swim u/s / weak attraction to VMG







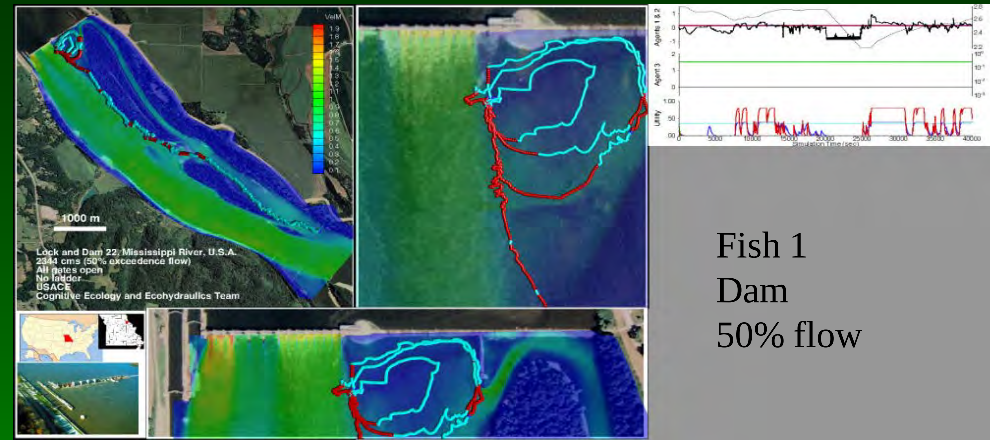
Telemetry

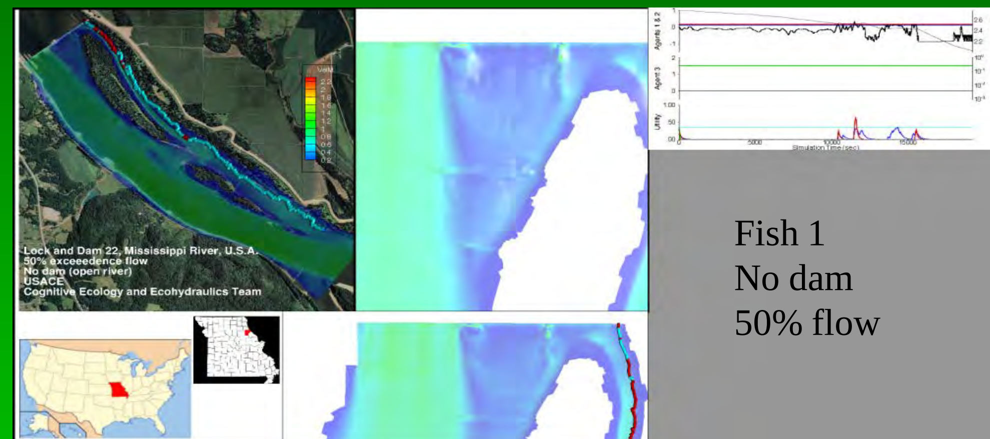


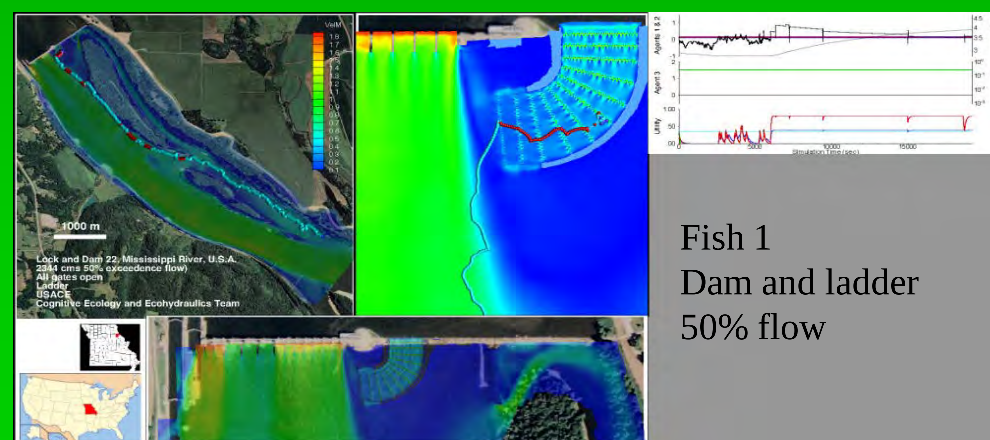
- **155 shovel-nosed sturgeon were tagged with Vemco acoustic tags** **(Tripp and Garvey 2011)**
- **Over four years, ~60% of the sturgeon detected downstream were detected upstream. Most were thought to pass the dam during the spring time.**
- **Observed to concentrate in eddy near dam and along east shoreline**

Scenarios

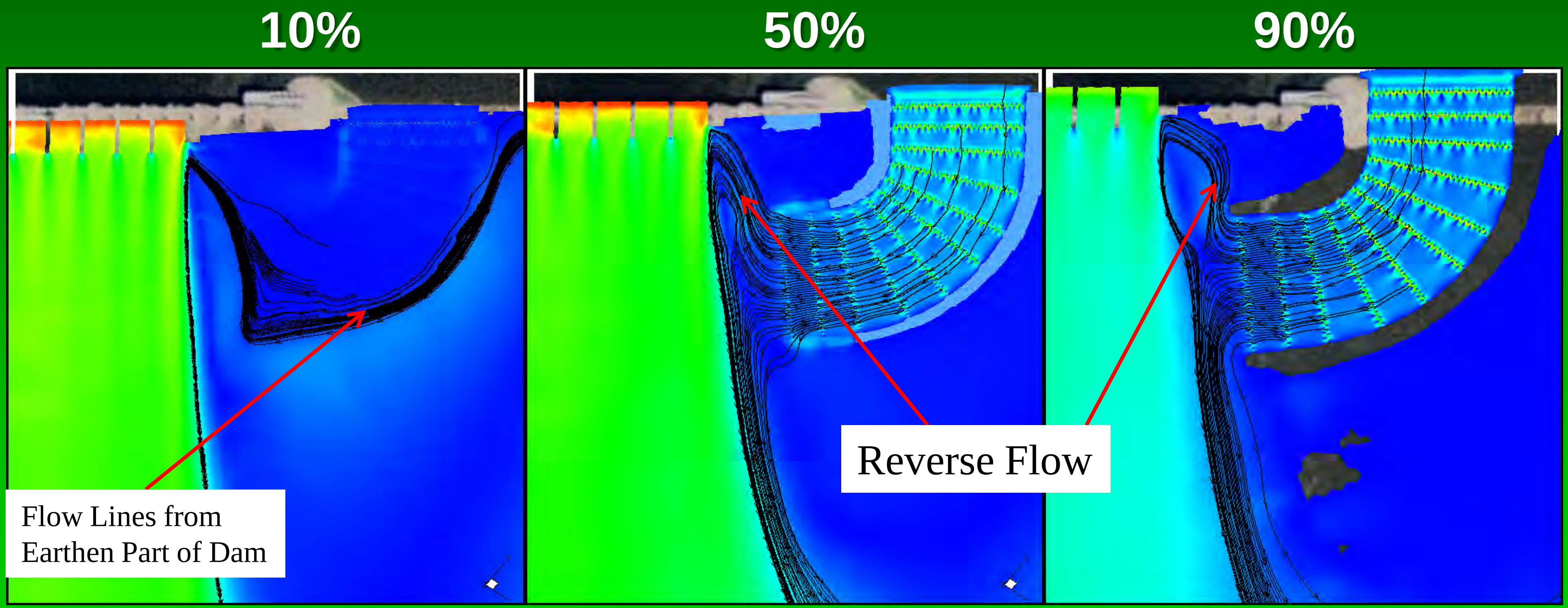
- Five flows (90% to 10% exceedance)
- Three configurations
  - Existing dam with no ladder
  - Existing dam & proposed ladder
    - Constant 1.49% of river flow (16.6 to 85.8 cms)
  - No dam & existing levied channel
- All gates open with equal flow
- 500 fish output at 10 second time step
- Descriptive statistics
  - Path length (m)
  - Swim speed (BL/s) (Hoover et al. 2011
  - Fatigue (%) (Katapodis and Gervais 2011)
  - Swim angles (degrees)
  - Spatial distribution
  - Passage (%)







Pattern in Passage Results - Useful Results



Interim Conclusions

Seems to Have Worked – juvenile salmon & adult sturgeon passage applications successful

Therefore:

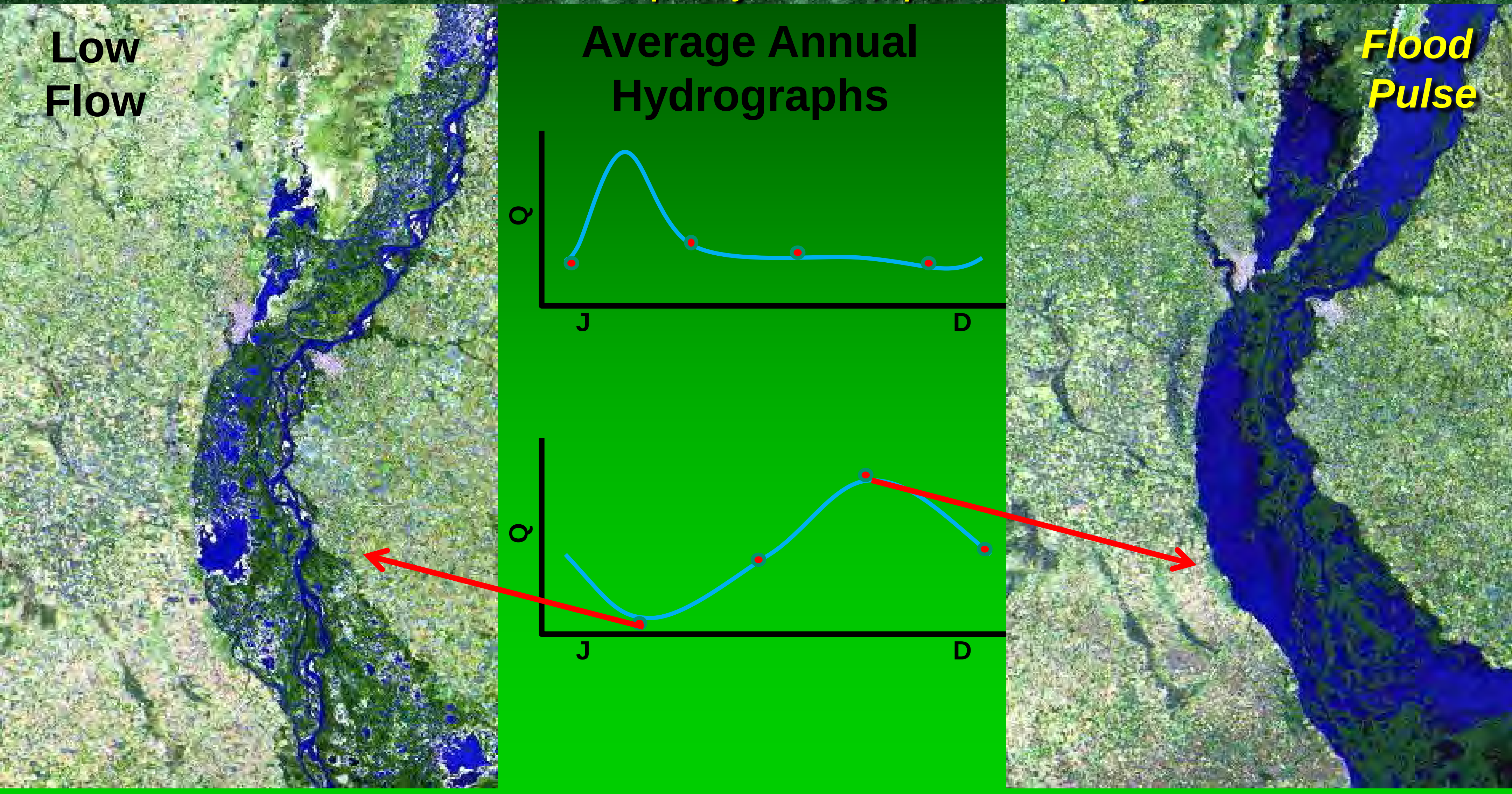
- "Solution Space" continues to feature velocity magnitude and velocity magnitude gradient with accommodations for fish size, model dimensionality & mesh attributes in a nonlinear manner.
- Limited number of upstream / downstream movement strategies / reduces study needs

River Machine & Hydrologic Engine

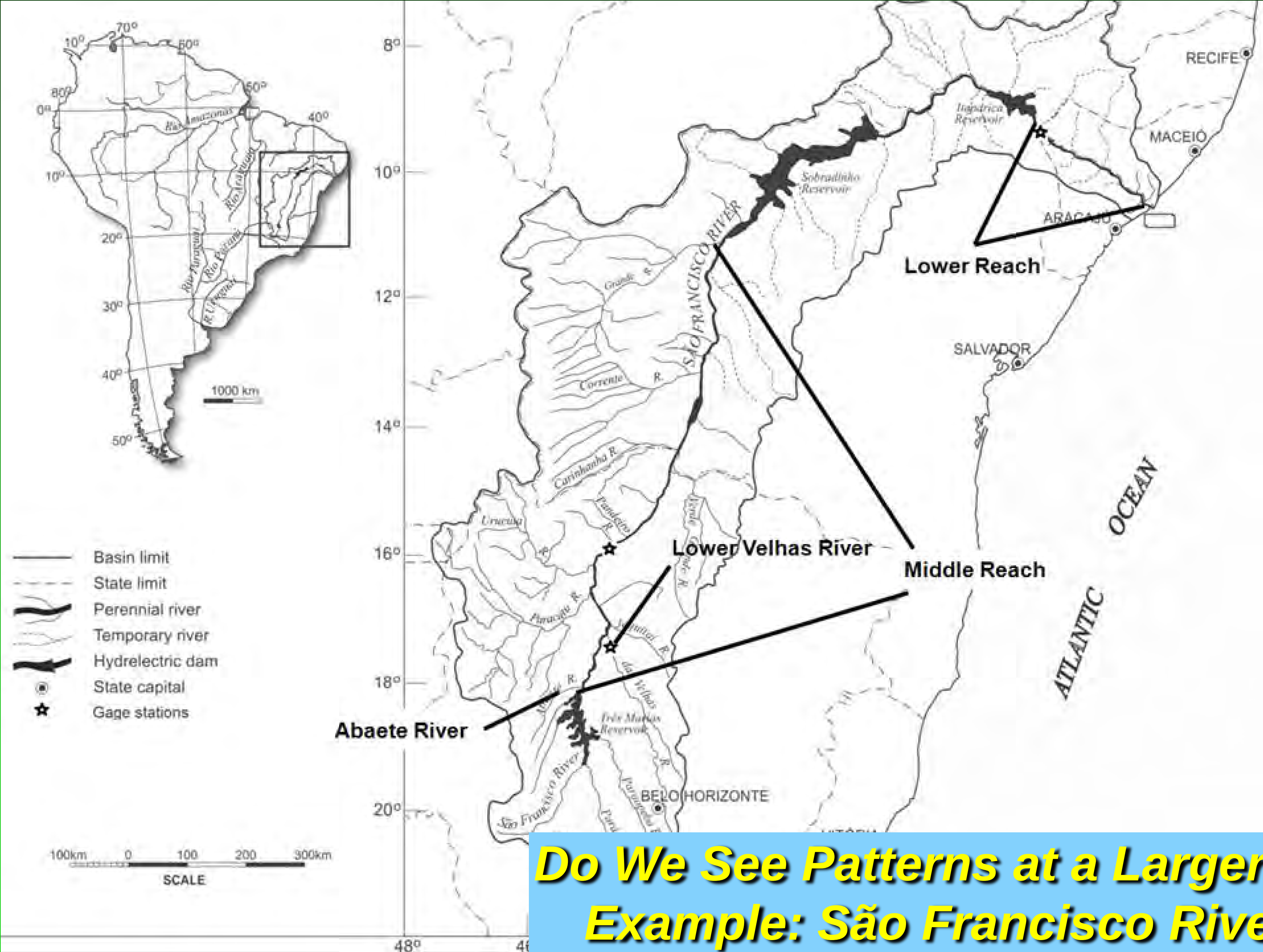
(Slope => Applied Force):

What the Machine Does: 1) Erosion/Deposition driven by shear (strain – VGM)
2) Transport/residence time driven by velocity magnitude

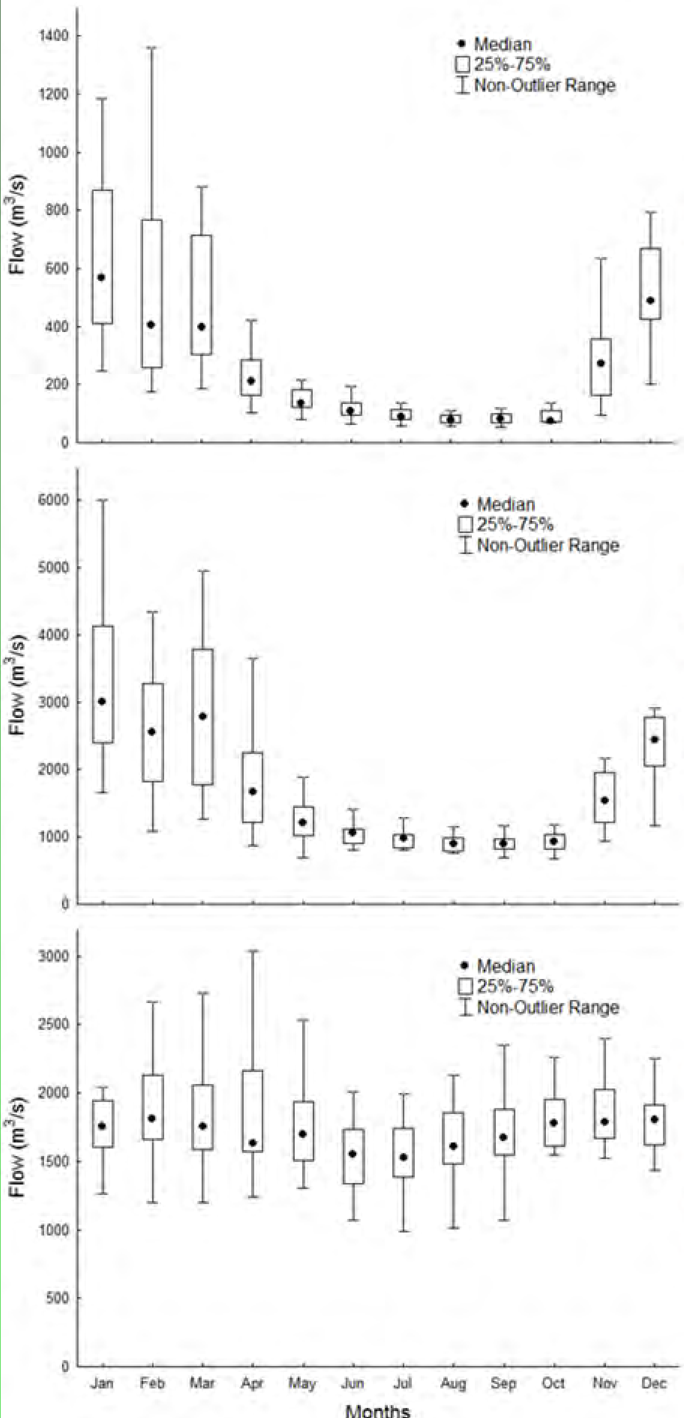
Creates immense temporally variable, spatial complexity



Do We See Patterns at a Larger Scale?
Example: São Francisco River, BR



Monthly Hydrograph São Francisco River, BR



Velhas River – Unregulated

Middle São Francisco River – regulated but with significant downstream tributary inflow

Lower São Francisco River - highly regulated and no significant tributary inflows

Hydrologic & Fisheries Characteristics of Three Floodplain Reaches São Francisco Basin, Brazil

Summarized from Sato & Godinho 2003; Pompeu & Godinho, 2006; Santos, 2009; Santos et al, 2009

	São Francisco River Floodplain regions		
	Lower Velhas River	Middle São Francisco River	Lower São Francisco river
Elevation	490-510 m	430-500 m	10-90 m
Number large reservoirs upstream	zero	one	eight
Flow regulation	insignificant	moderate	severe
Floodplain fish biodiversity	61 species	48 species	48 species
Large migratory fish extinction?	no	no	yes
Status of fisheries	No information	decreased catches	decreased catches

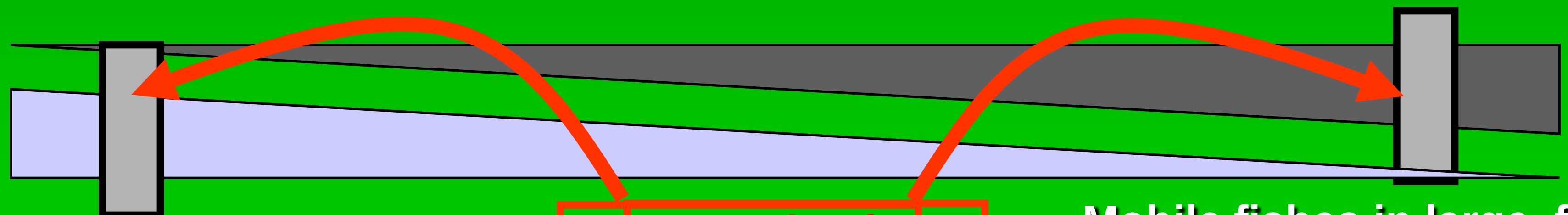
Reconciling Fish Habitat Concepts: Small Streams and Large Rivers

Place-Specific (resident) Activity
- Feeding at a feeding station
- Spawning at a specific area

Local Hydraulic Variables
- Absolute values critical
- Background less important

Place-Searching (Itinerant) Activity
- Locating a new feeding station
- Locating resource caches
- Finding a spawning site

Roadmap Hydraulic Variables
- Absolute values less important
- Background very important



Resident fishes in small, hard-bottom, baseflow streams: e.g, darters, sculpins, trout

Numerical Fish Surrogate Models

HSI & Simple Hydraulic Habitat Tools

Mobile fishes in large, flood pulse rivers: e.g, sturgeon, paddlefish, salmon

Aristotle and First Principles
ELAMs and HSI Curves

IFIM Approaches – Deterministic
“Not very scientific”

NHG Approaches – Empiricist
“Not very incremental”

ELAMs –
Cognition
Behaviors
Sensory Biology
Scale Fidelity

The "River Machine", Function, Process, Large River Fishes, and Disturbance

Reduce system into fields

Flow Field

Geophysical Field

Biochemical Fields

Velocity
Magnitude
Vel Mag
Gradient

Scale Filter

Velocity
Magnitude
VM
Gradient

Flow Field

Geophysical Field

?

Biochemical Fields

Outcome: fish use "river machine" at system level

Outcome: fish cannot use "river machine" at system level

River Machine & Hydrologic Engine: Machine Supports Immense abundance and diversity of life

- **Illinois River – One of worlds most productive fisheries**
  - **– provided portion of protein needs of Chicago**
- **Mekong River – catch of ~2M metric tons**
  - **- provides protein needs of ~200,000 people**
- **Parana River – catch of 1,000 kg/hectare of sabolo**

Fluvial Dependent Fishes take advantage of the "free" work performed by the river
- couple their biology to basin processes
- access to hundreds of millions of tons of organic matter produced in large river basins / watersheds
- other taxons use this strategy?

"River Machine" Concept Ramifications

- **Pragmatic ramifications if true:**
  - **Same movement rule for all species (+secondary currents), with nuances for swimming speed & size, channel orientation (e.g., surface, thalweg, shoreline), fish anatomy & physiology, etc.**
  - **Reduces study needs to develop hydraulic criteria for fish passage design**
- **Conceptual ramifications if true apply to :**
  - **Environmental flow determination**
  - **Channel restoration actions**
  - **Nutrient management goals**
- **Goal – test the "River Machine" concept using the existing rule & calibrating/validating to a completely different species (shovel nose sturgeon -*Scaphirhynchus platorynchus*) and site (Mississippi River) using fewer data.**

Why Engineers & Ecologists Must Collaborate
Philosophical / Conceptual / Scientific Reasons

- **"….in seeking regularity and focusing on the most salient features in their environment, in order to endure and thrive, animals have empirically discovered the laws (i.e., physical) of nature."**

(Kalmijn, A. J. (2000). Detection and processing of electromagnetic and near-field acoustic signals in elasmobranch fishes. Philosophical Transactions of The Royal Society of London series B, 355(1401), 1135-1141.)

- **Ecologists accurately describe/predict ecological response**

- **Engineers accurately describe/predict flow fields**

- **Understanding how animals "endure and thrive" requires integration of tools from both disciplines – accurate forecasting requires seamless integration**

Conclusions

Seems to Have Worked –

- Successfully calibrated to tagging data, matched observations, and got insightful results

Therefore:

- "Solution Space" continues to feature velocity magnitude and velocity magnitude gradient with accommodations for fish size, model dimensionality & mesh attributes in a nonlinear manner.
- Limited number of upstream / downstream movement strategies / reduces study needs
- River Machine concept supported – at least for fluvial dependent large river fishes
  - Fish Passage
  - River Restoration
  - Nutrient Management Approaches
  - Good Supplement / Alternative for HSI–based tools

Thank you!

Questions?

Comments?

Note: No animals were harmed or killed
In the preparation of this presentation